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Truck Transport Results / Progress on Rail Test

SNL-BAM Workshop
7 October 2014
Paul McConnell
SAND2014-18948 PE

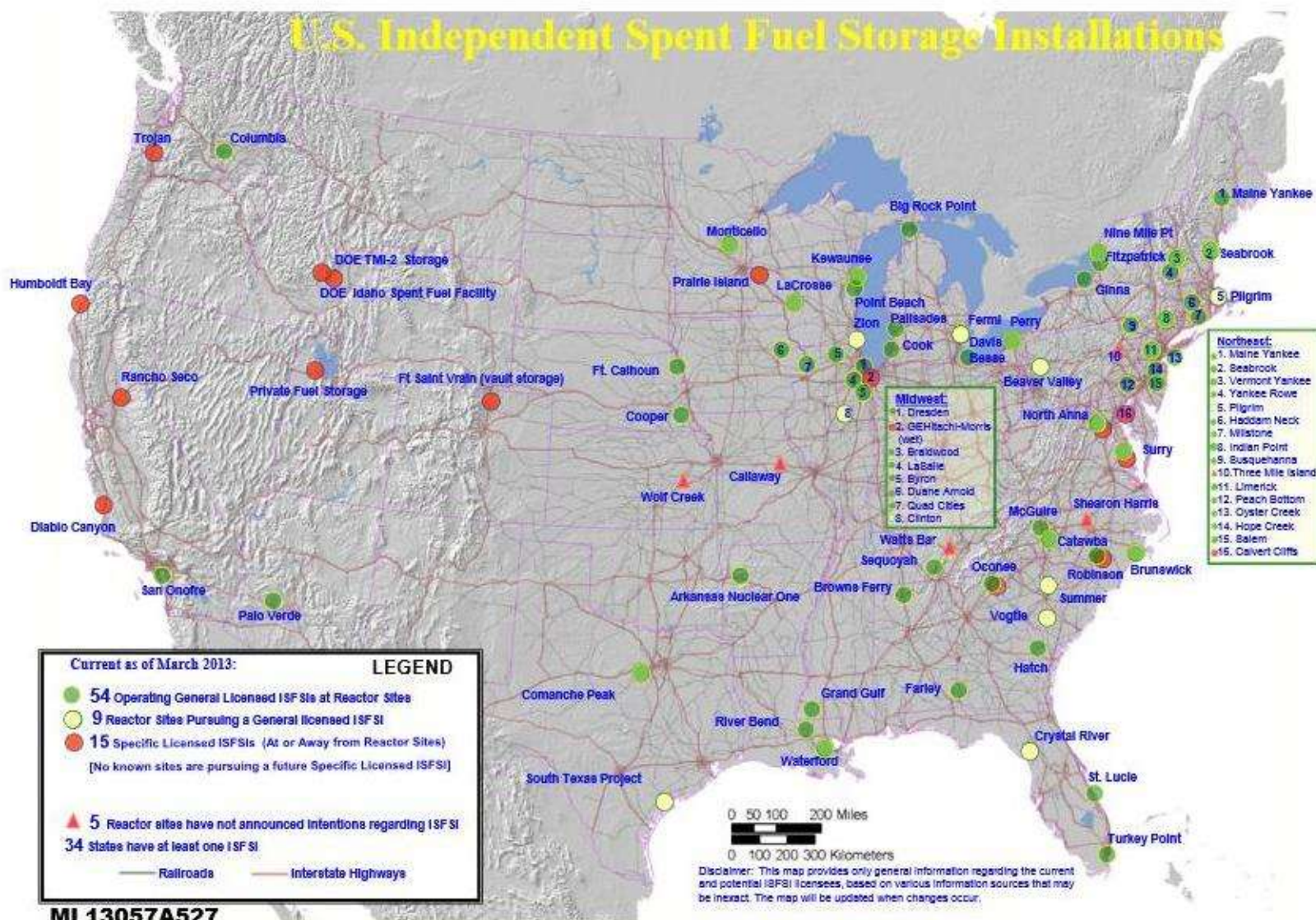


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What we think we know

- **The strains measured in the test program were in the micro-strain levels** – well below the elastic limit for either unirradiated or irradiated Zircaloy-4.
- Based upon the test results, which simulated normal vibration and shock conditions of truck transport, **strain- or stress-based failure of fuel rods during normal transport seems unlikely.**
- Strains on irradiated rods may be less than strains measured on unirradiated tubes.
- Normal conditions of truck transport are more severe than rail.

ISFSI Locations



ML13057A527

<http://www.enviroreporter.com/wp-content/uploads/2013/10/NRC-map-of-Independent-Spent-Fuel-Storage-Installations.jpg>

Lots of Assemblies to be Stored & Transported

22

Fuel Cycle Potential Waste Inventory for Disposition
July 2012

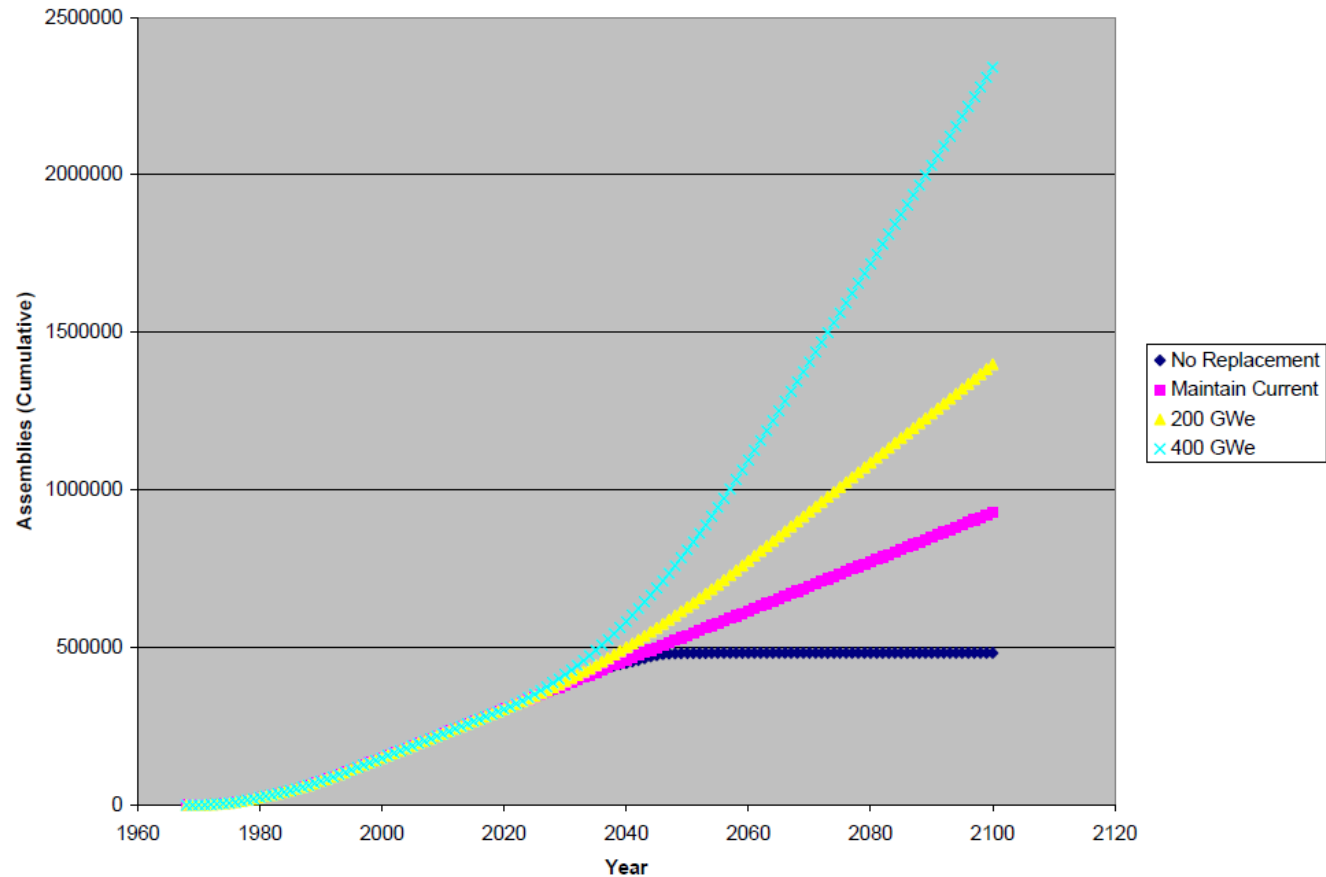


Figure 3-3 Cumulative UNF Assemblies Discharged for the No Replacement, Maintain Current, 200 GWe/yr, and 400 GWe/yr.

Transportation



NAC-MPCs (MPC-36 canisters)



NAC-STC rail cask

Courtesy Yankee Rowe



Yankee Rowe



Heavy-haul truck required to get to railhead

Courtesy Yankee Rowe



Hoosac Tunnel

See: http://en.wikipedia.org/wiki/Hoosac_Tunnel

Transportation



Parking lot for heavy-haul truck
access to railhead!



Railhead, Portland, Conn.
near Connecticut Yankee

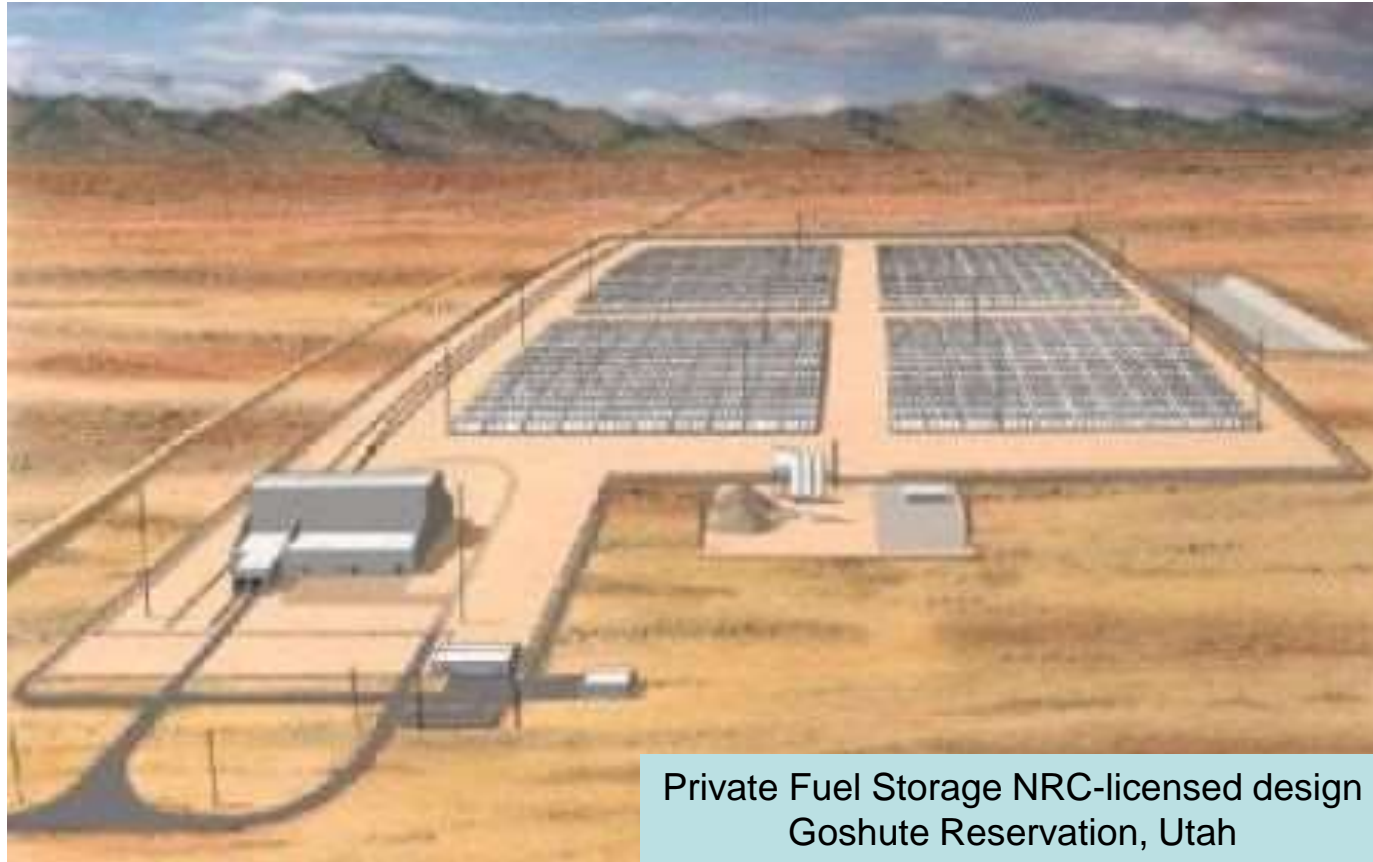
Barge transport, Connecticut River
(Connecticut Yankee pressure vessel)
Courtesy Connecticut Yankee



Connecticut Yankee
barge slip site



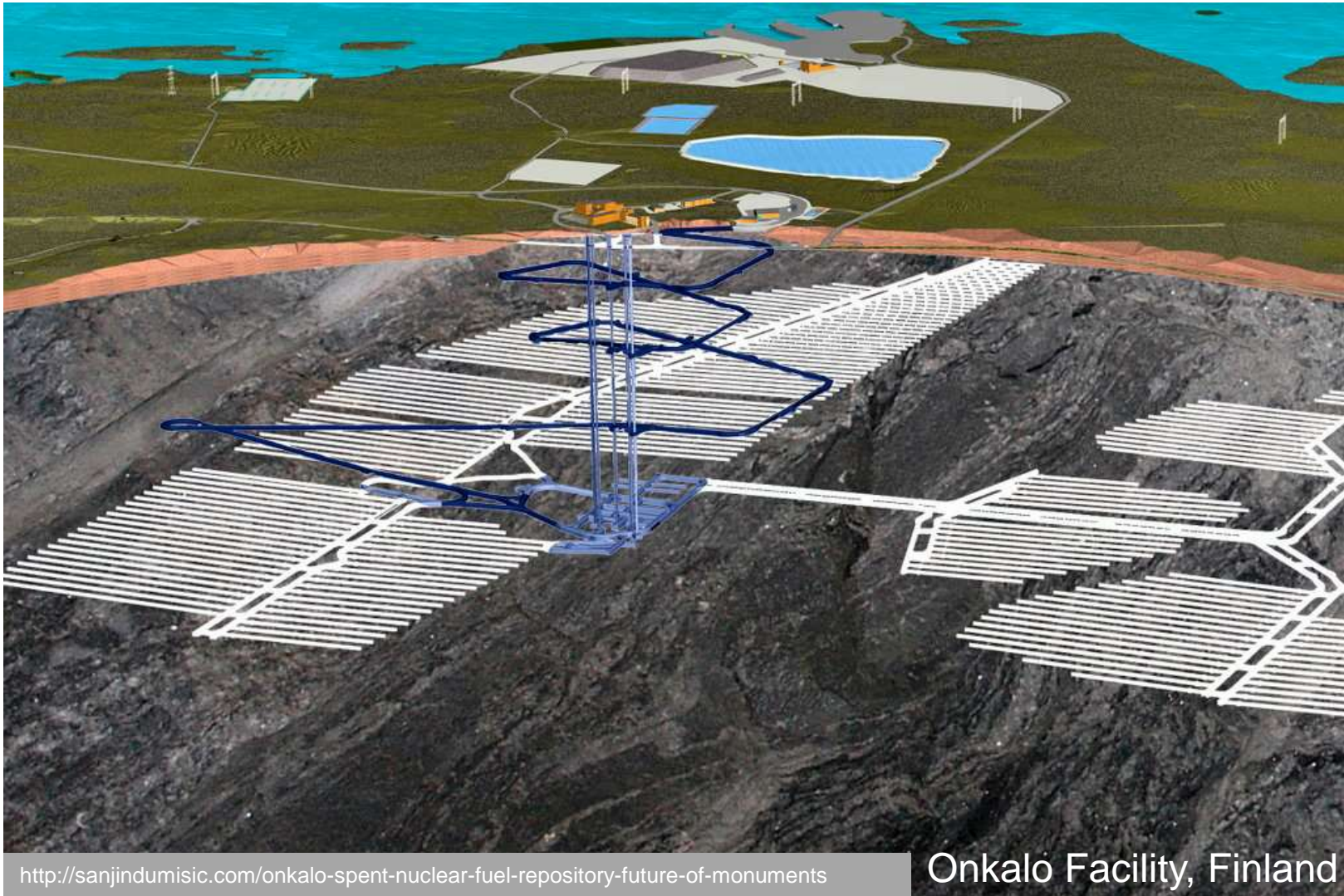
Central Storage Facility



Private Fuel Storage NRC-licensed design
Goshute Reservation, Utah

http://www.world-nuclear-news.org/WR-Rethink_on_Utah_used_fuel_storage_project-0408104.html

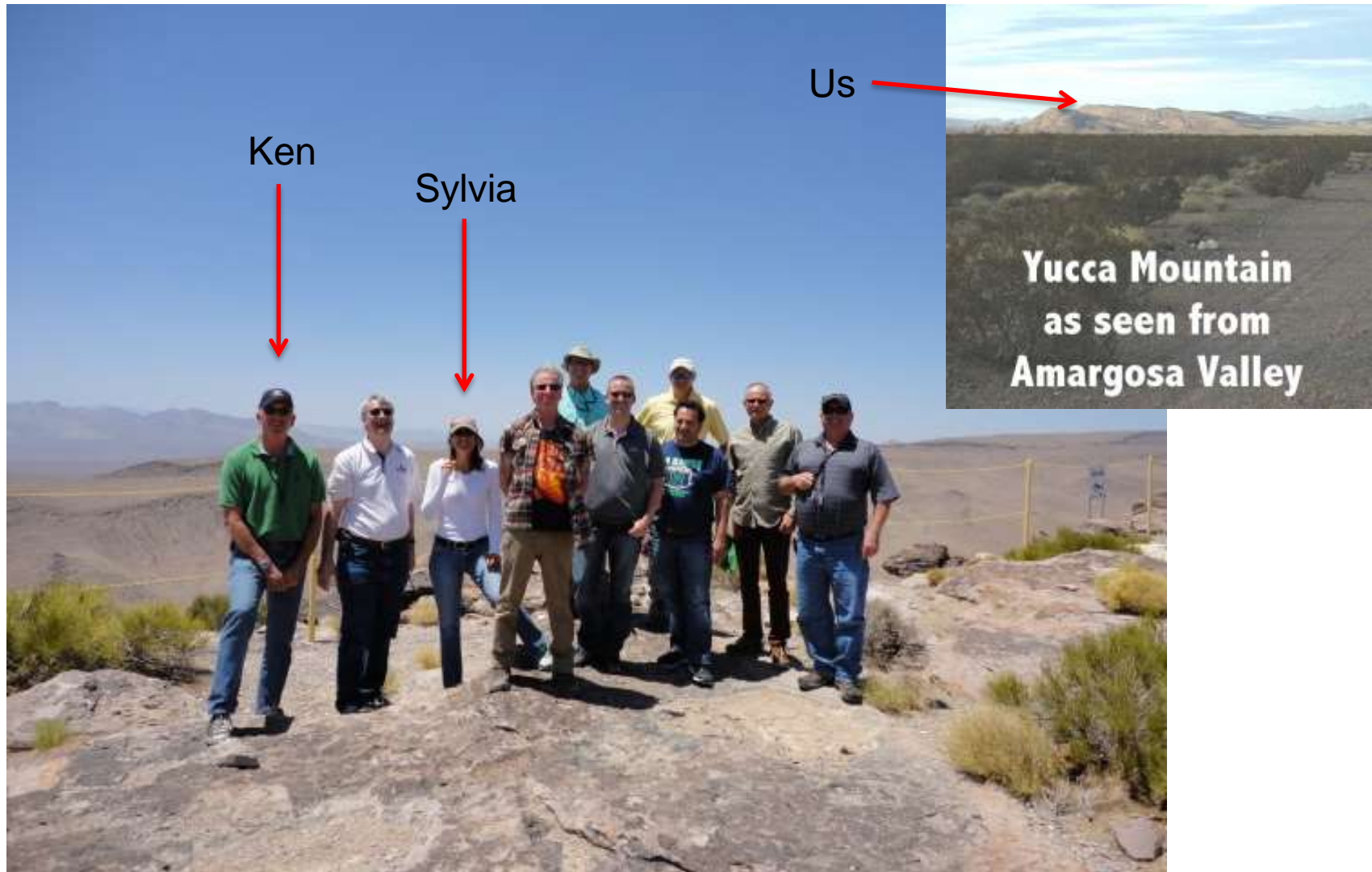
Repository



<http://sanjindumisc.com/onkalo-spent-nuclear-fuel-repository-future-of-monuments>

Onkalo Facility, Finland

Not a Repository



There Will Be Lots of High Burnup Assemblies

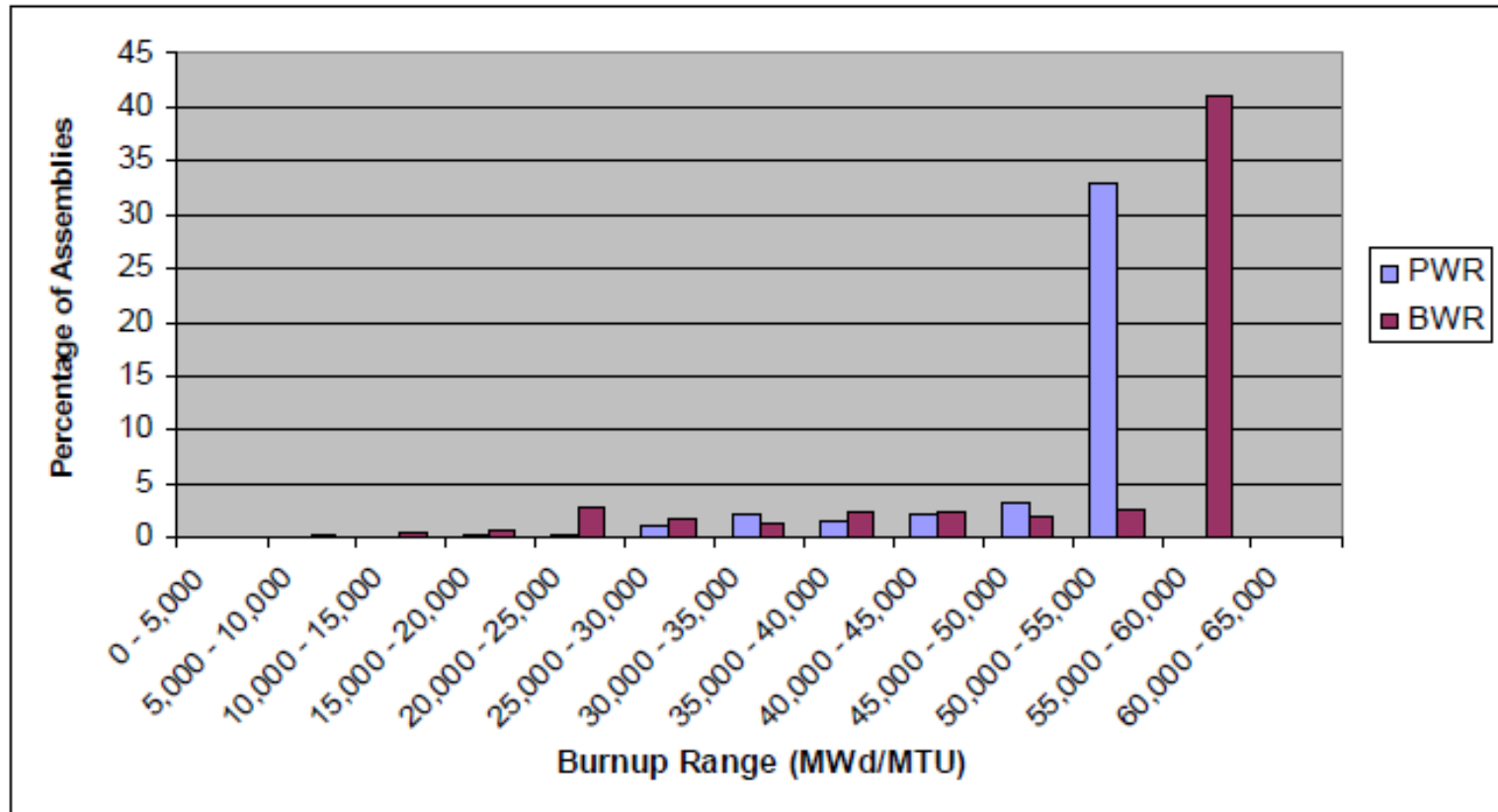
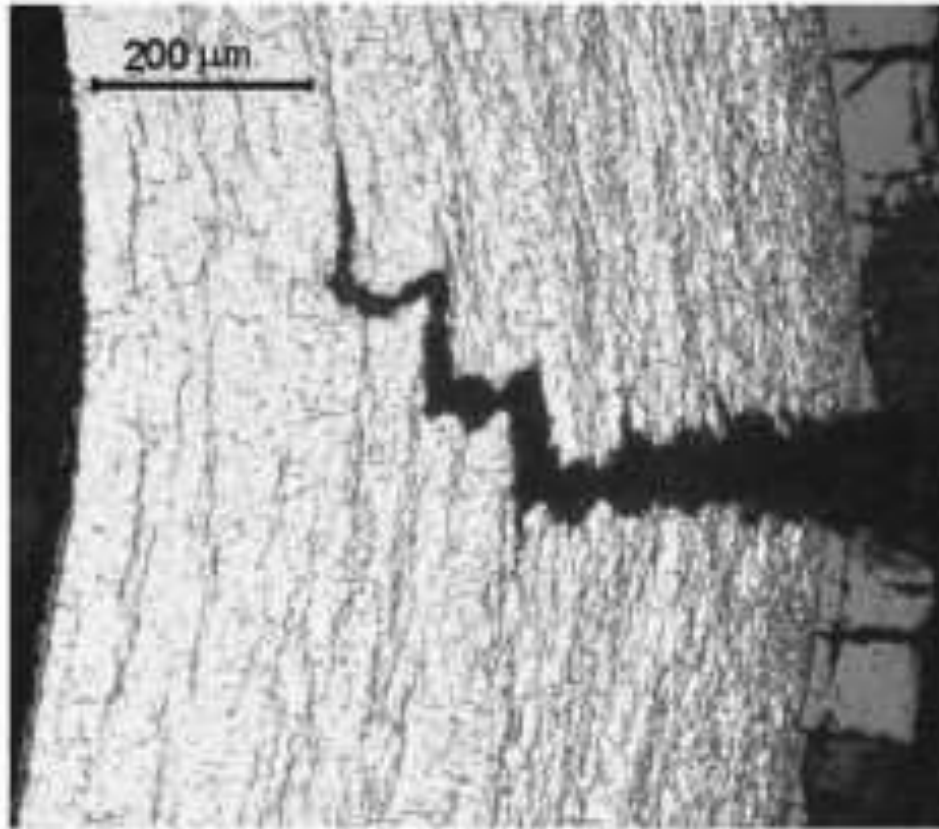


Figure 3-7 Percentage of Assemblies per Burn-up Range – Maintain Current Nuclear Generation Case

Motivation for assembly testing

- Federal Regulations require an assessment of “*Vibration* - Vibration normally incident to transport”...
...imposed on transport packages and contents during “normal conditions of transport”. (10CFR71.71)
- The NRC has approved normal transport of low burnup spent fuel.
- However, the technical community needs to [establish a technical basis](#) to demonstrate that high burnup fuel rods can withstand all normal conditions of transport.
- Vibrations and shocks have been measured on truck trailers and railcars but not directly on fuel assemblies, baskets, or fuel rods.

In other words, could Zircaloy cladding fracture during normal conditions of transport?



<http://sanonofresafety.org/nuclear-waste/>

Application of Fuel Assembly Test Results (1)

The margin of safety between the applied loads on fuel rods during transport and the material properties of Zircaloy rods has not been quantified.

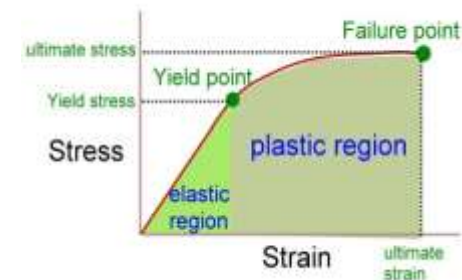
The SNL assembly tests provide data – the applied stresses on the rods - related to the issue of the margin of safety:

applied rod stress_{normal transport}



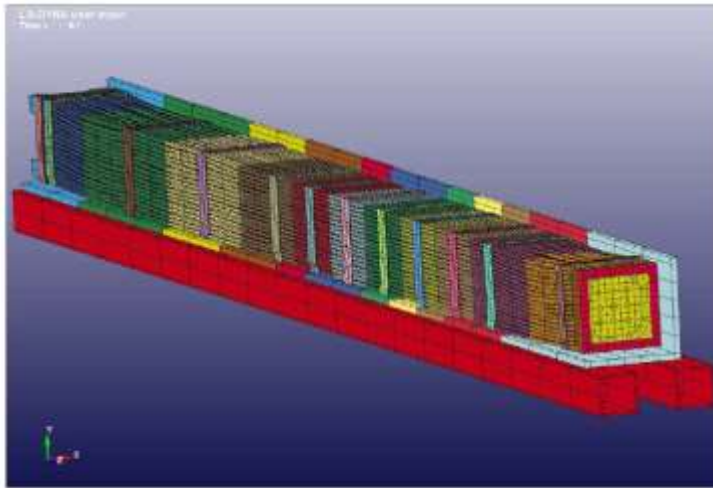
Material property test programs at other national laboratories shall measure properties of high burnup cladding:

yield strength_{cladding}



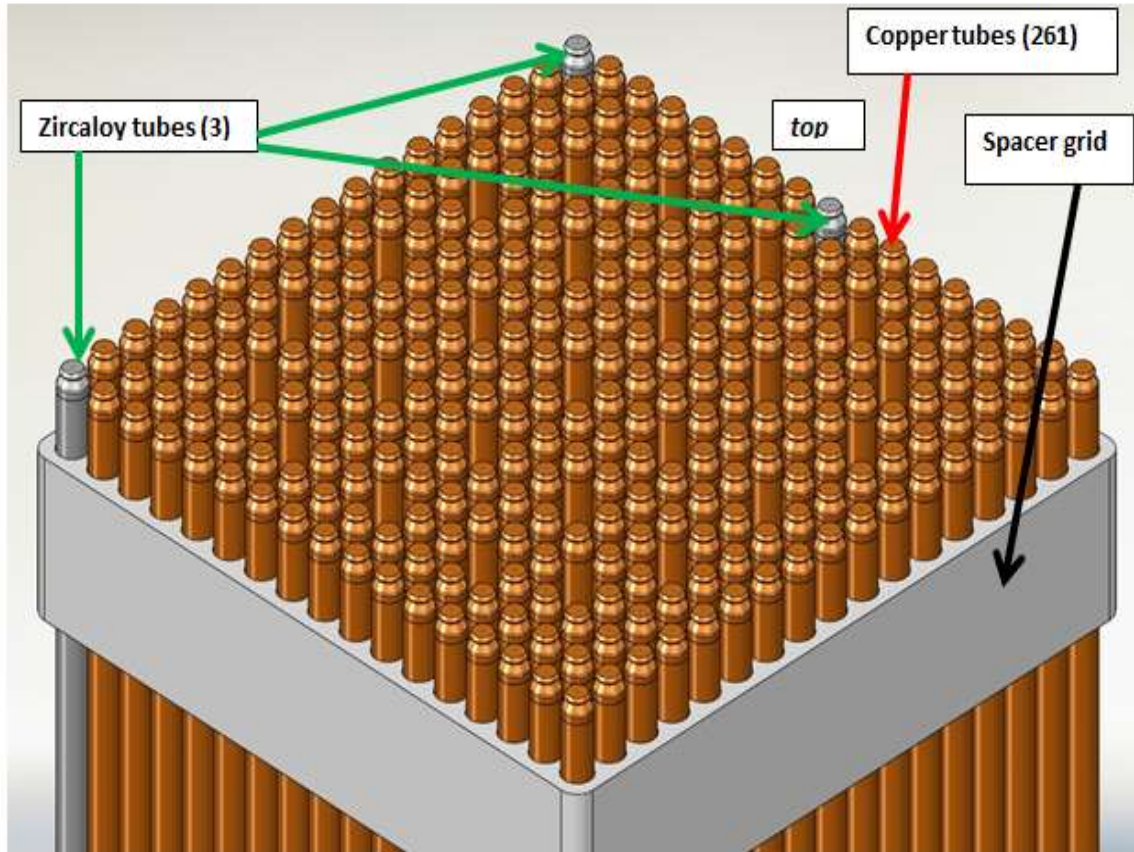
Application of Fuel Assembly Test Results (2)

- The data from the assembly tests will be used to validate finite element models of fuel assemblies.
- The validated models can be used to predict the loads on fuel rods for other basket configurations and transport environments, particularly rail.



FUEL ASSEMBLY SHAKER TEST SIMULATION, Klymyshyn, et al., PNNL,
FCRD-UFD-2013-000168, May 2013

SNL Experimental 17x17 PWR Assembly



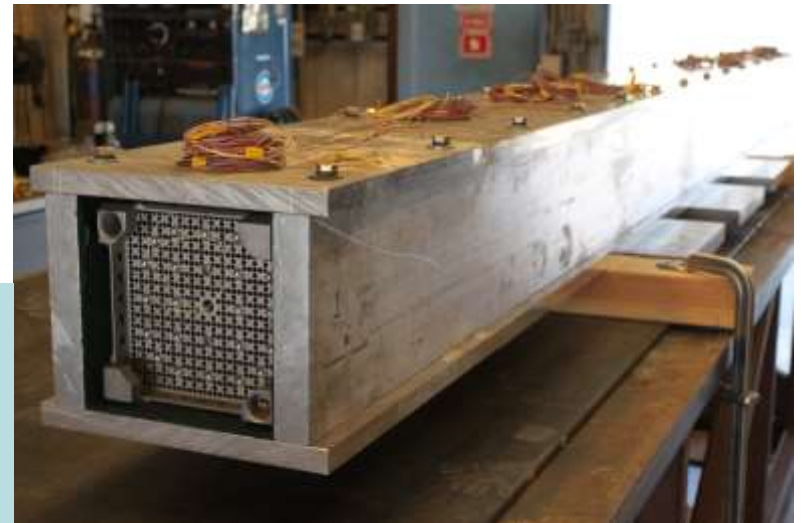
Only Zircaloy rods were instrumented with strain gauges and accelerometers

Isometric View of Fuel Rods
(Top Nozzle and Basket not shown)

Basket/Assembly Test Unit

- The test unit included an assembly and a basket.
- The basket is based upon the geometry of the NAC-LWT truck cask PWR basket.
- The assembly was placed in a basket which was placed on 1) a shaker and subsequently 2) a truck trailer.
- The assembly had the same freedom of motion within the basket as it would have in an actual cask.

- 6061 Aluminum Basket
- Sides 1.5 inches thick
- Top/bottom 1 inch thick
- Length 161.5 inches
- Weight 837 pounds



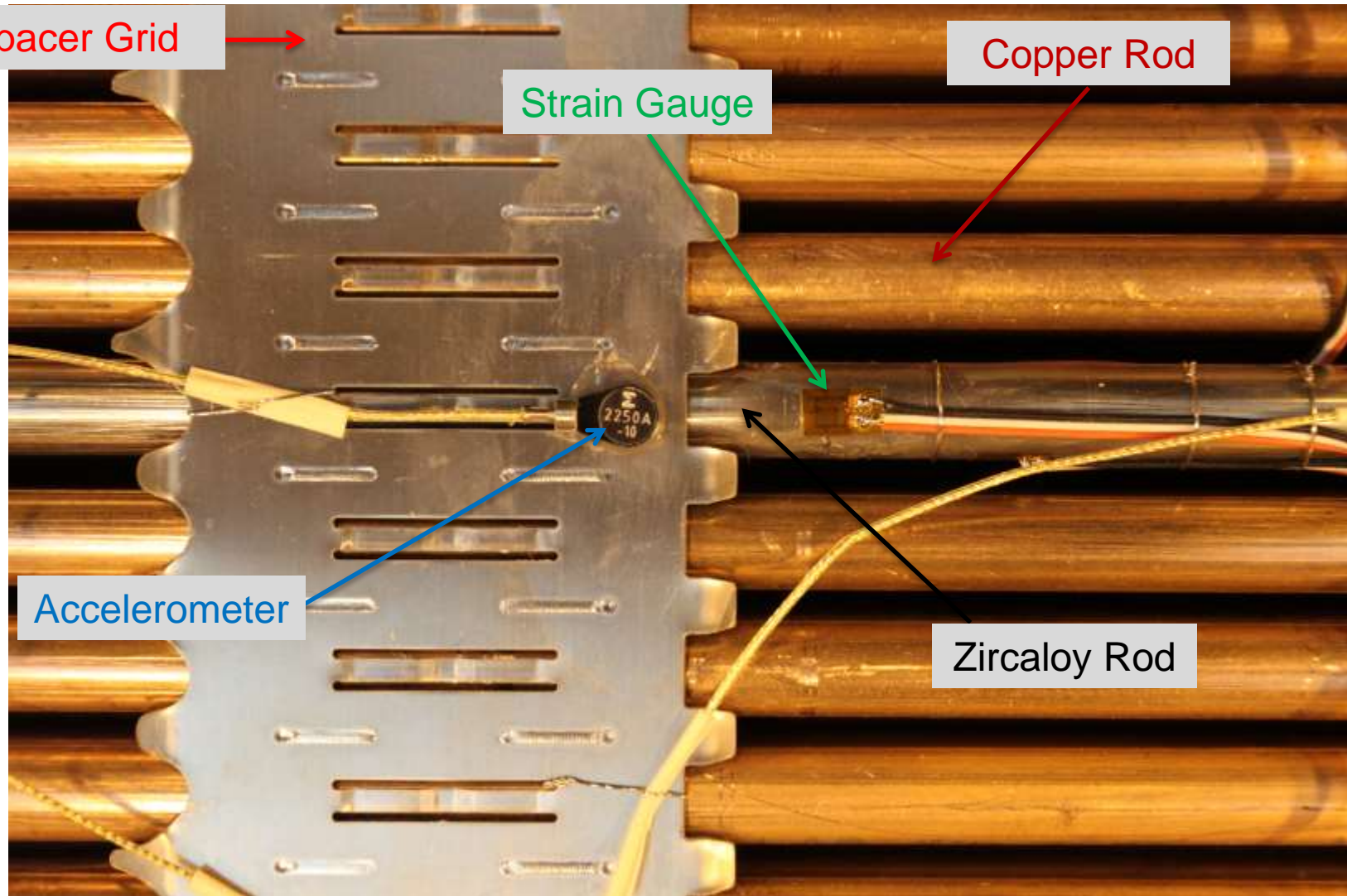
Lead Rod within Copper Tube to Simulate Mass of UO_2 (Zircaloy-4 tubes also contained Lead)



Initial Dimensions for Simulated Copper Fuel Rod Mock-up	
	Cu
OD (in.)	0.3750
ID (in.)	0.3120
Thickness (in.)	0.0315
Sample Length (in.)	24.0000
Clearance Between Cu & Pb	0.0300

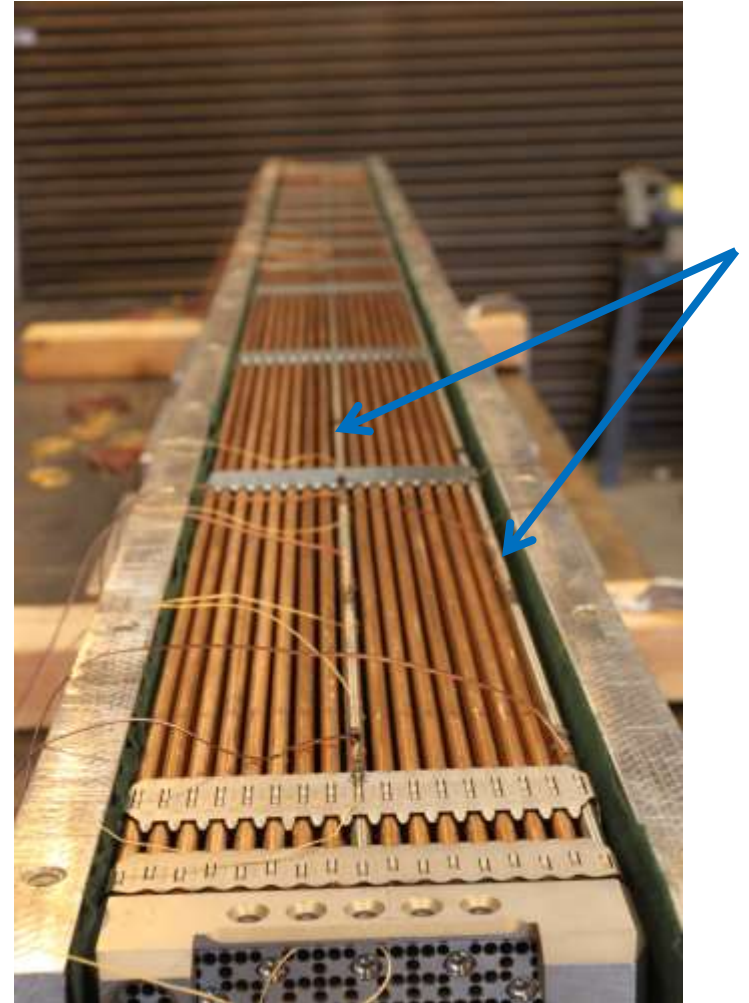
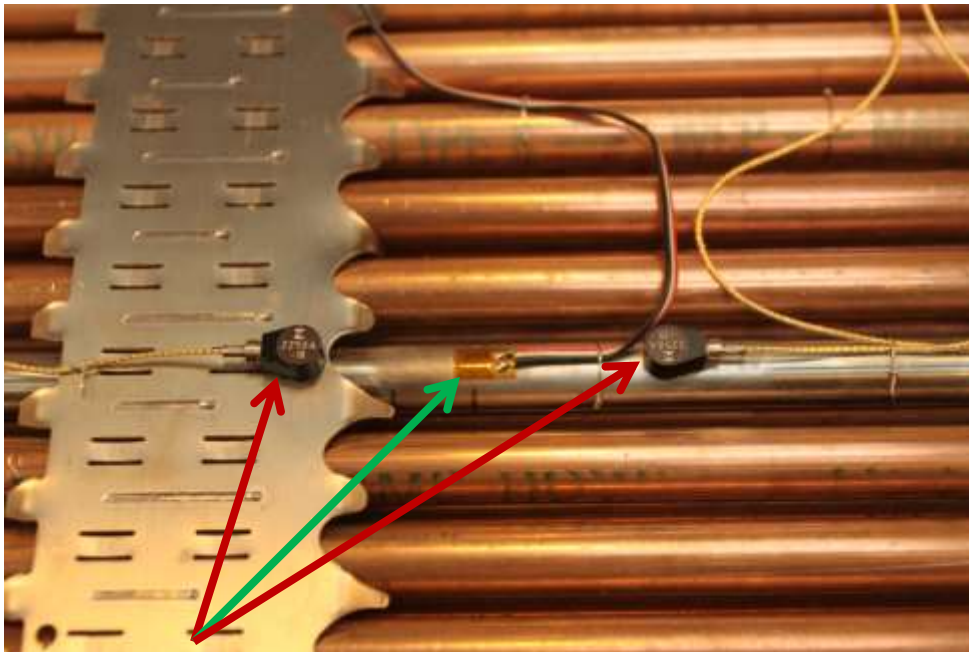


Uniaxial Accelerometer and Strain Gauge on Test Assembly



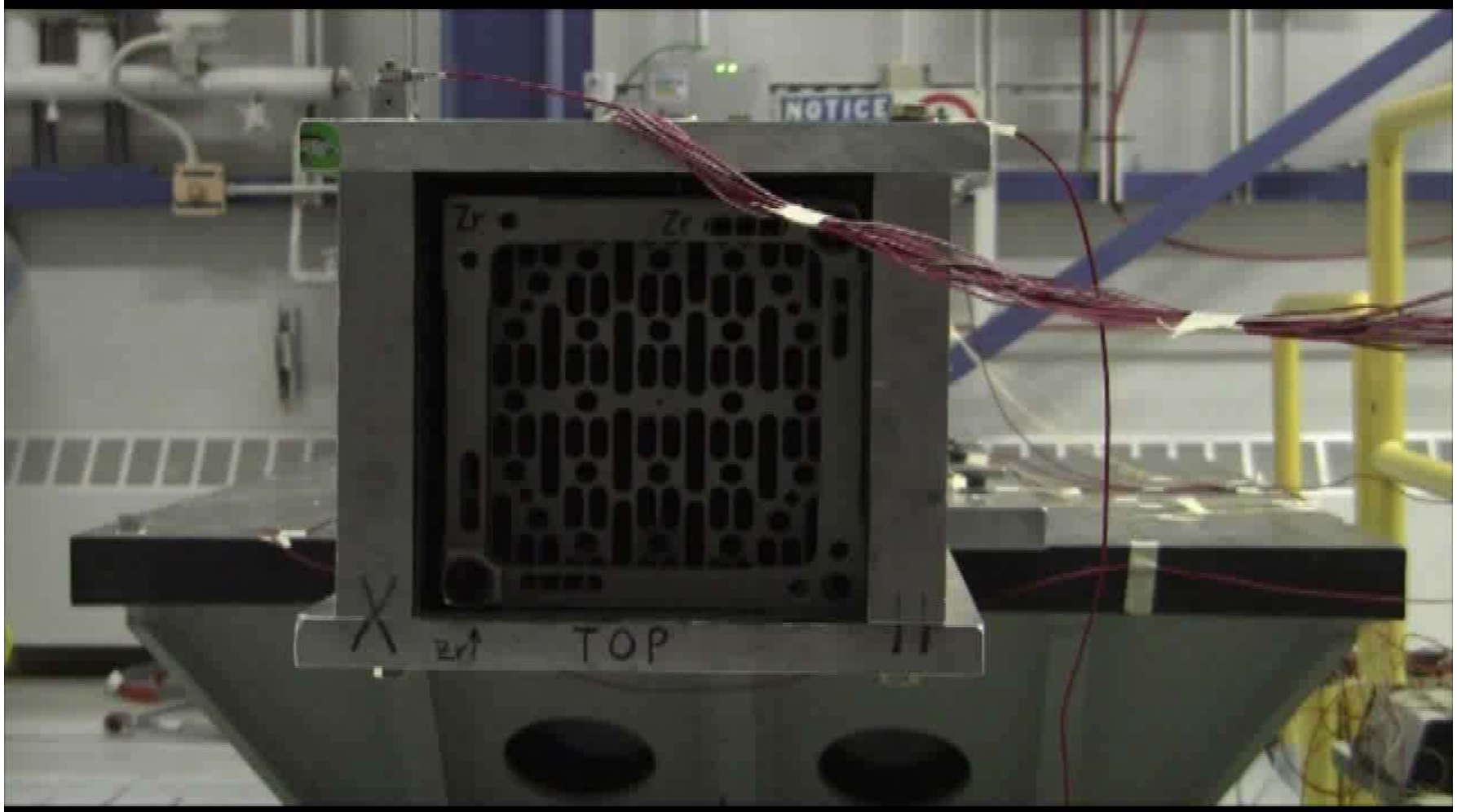
**Left: Accelerometers and Strain Gauge on Top-Center
Zircaloy Tube and Spacer Grid**

**Right: Assembly within Open Basket. Note the two Zircaloy-4 rods
with instrumentation attached**



Shaker Shock Test Video

Top-end view of assembly in basket



Maximum Micro-strains on Zircaloy Fuel Rods during Shaker Shock Test – *Strains are very low*

Maximum Strains on Zircaloy Fuel Rods, Shock Test #1			
Rod Location	Assembly Span	Position on Span	Maximum Strain (µin./in.)
Top-middle rod	Bottom-end	Adjacent to spacer grid	90
Top-middle rod	Bottom-end	Mid-span	131
Top-middle rod	Bottom-end	Adjacent to spacer grid	171
Top-middle rod	Mid-assembly	Adjacent to spacer grid	104
Top-middle rod	Mid-assembly	Mid-span	97
Top-middle rod	Top-end	Adjacent to spacer grid	127
Top-middle rod	Top-end	Mid-span	199
Top-middle rod	Top-end	Adjacent to spacer grid	70
Top-side rod	Bottom-end	Adjacent to spacer grid	54
Top-side rod	Bottom-end	Mid-span	107
Top-side rod	Top-end	Mid-span	117
Top-side rod	Top-end	Adjacent to spacer grid	113
Bottom-side rod	Bottom-end	Mid-span	62
Bottom-side rod	Bottom-end	Adjacent to spacer grid	121
Bottom-side rod	Mid-assembly	Adjacent to spacer grid	110
Bottom-side rod	Mid-assembly	Mid-span	115
Average of All Strain Gages			112
Average Top-middle Rod			124
Average Top-side Rod			98
Average Bottom-side Rod			102
Average Bottom-end Span			105
Average Mid-assembly Span			107
Average Top-end Span			125
Average Mid span			118
Average Adjacent to Spacer Grid			107

← maximum

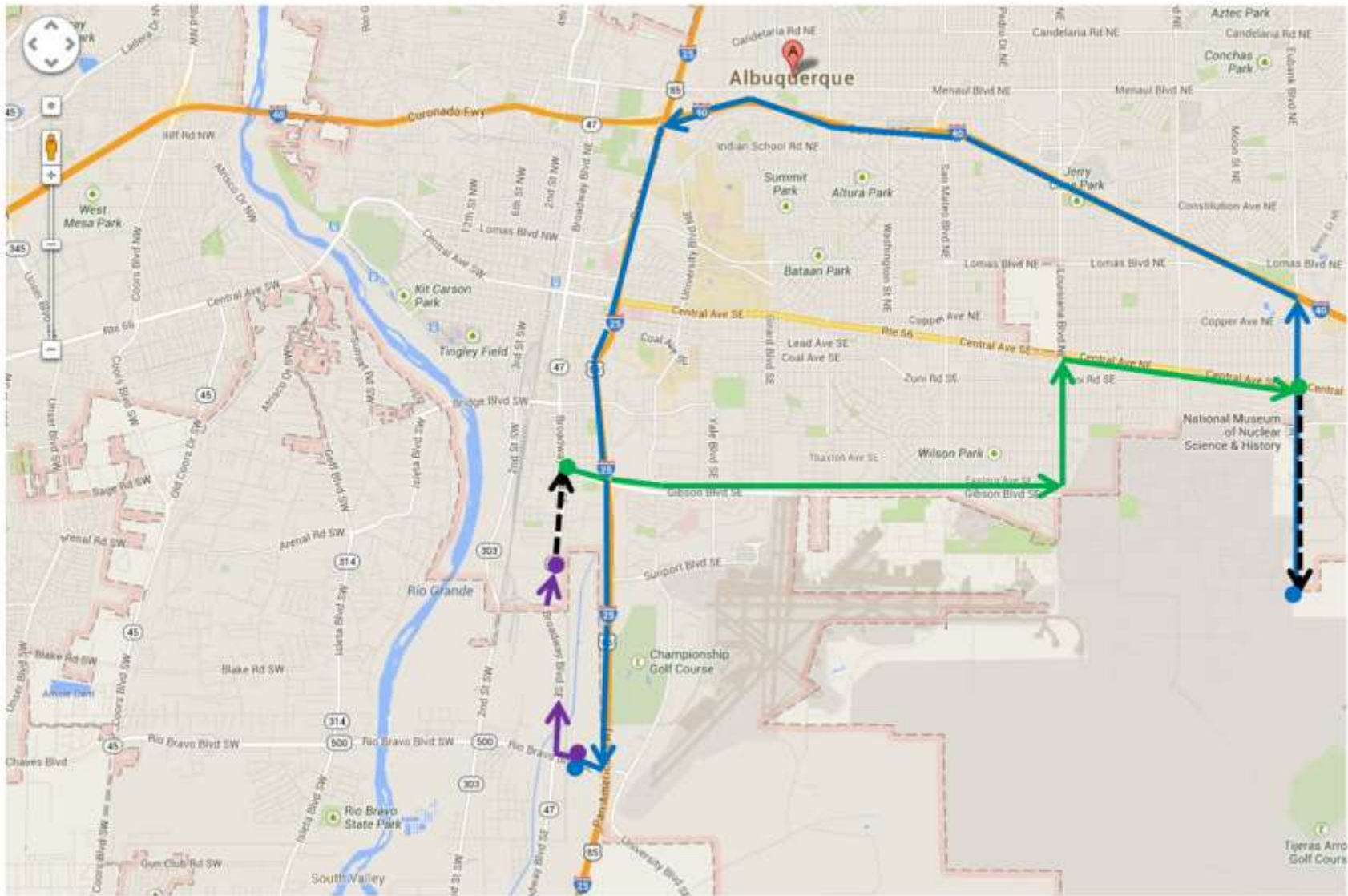
← average maximum

Test Unit on Concrete Blocks on Trailer



Truck Test Route

65 km in Albuquerque area



Range of Road Conditions



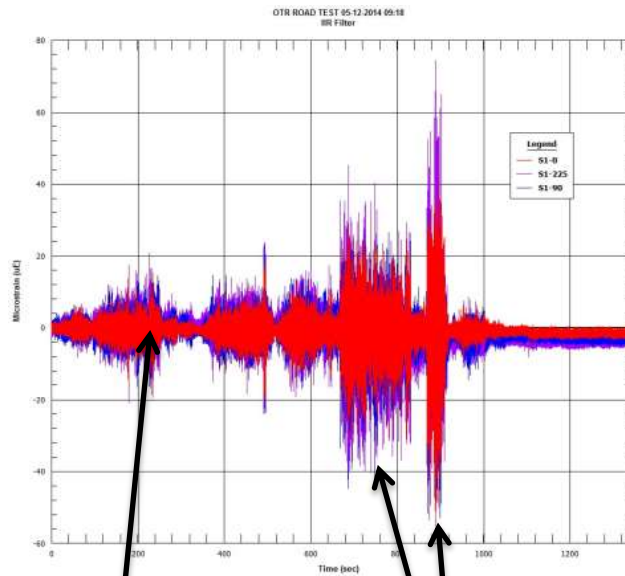
Route included railroad crossings...



...and rough dirt roads



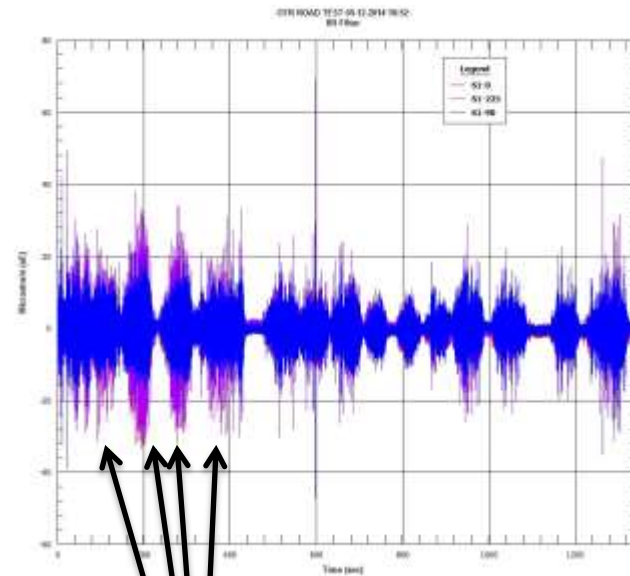
Strains measured on instrumented rod



dip on Area III Access Road



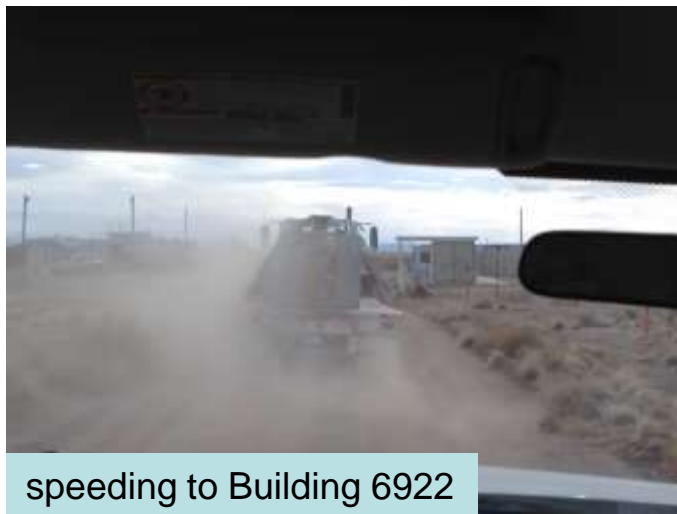
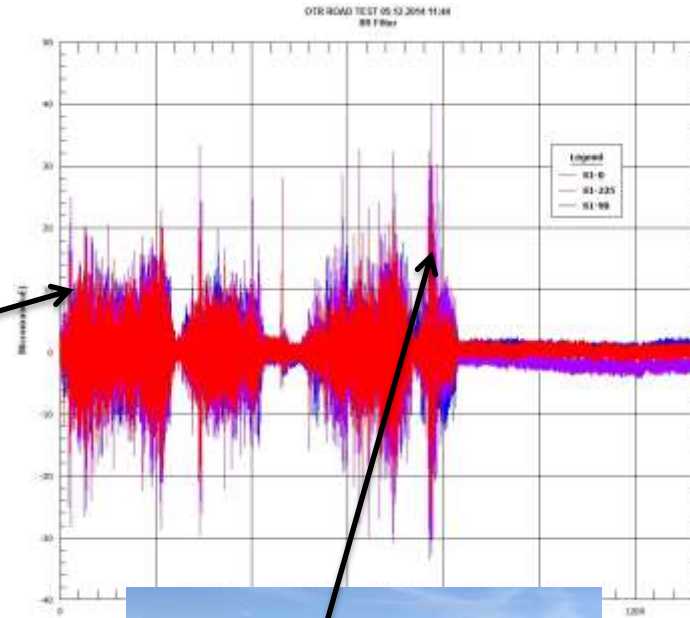
Poleline Road



Gibson Blvd.

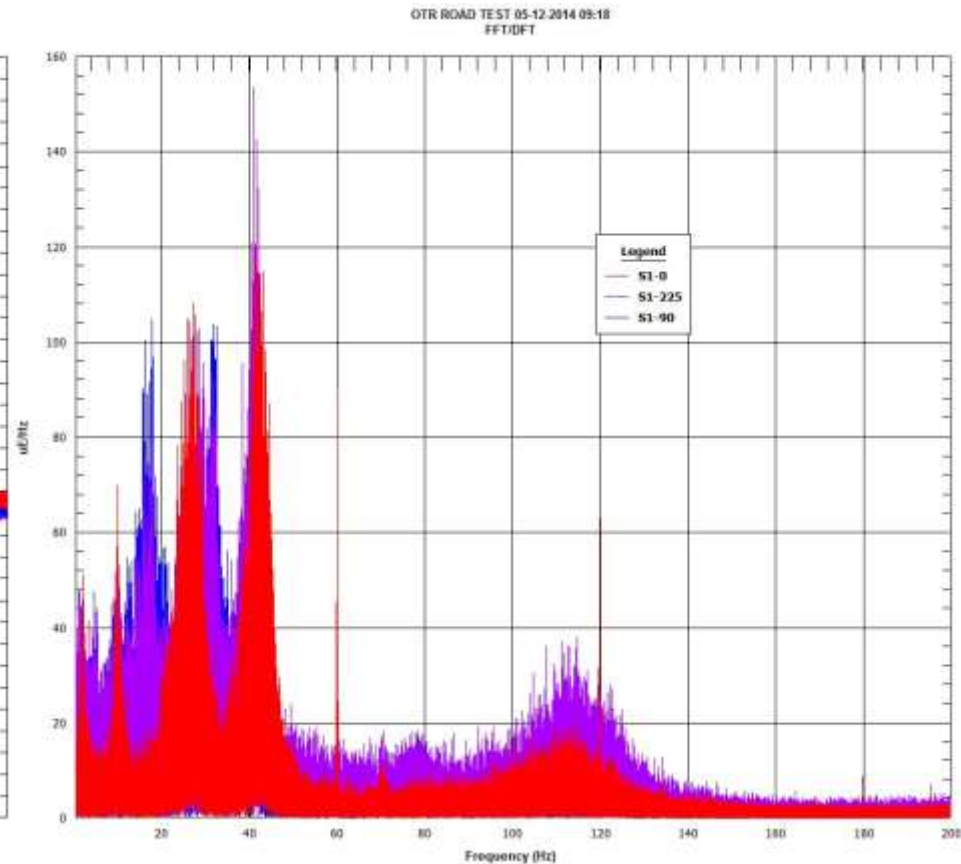
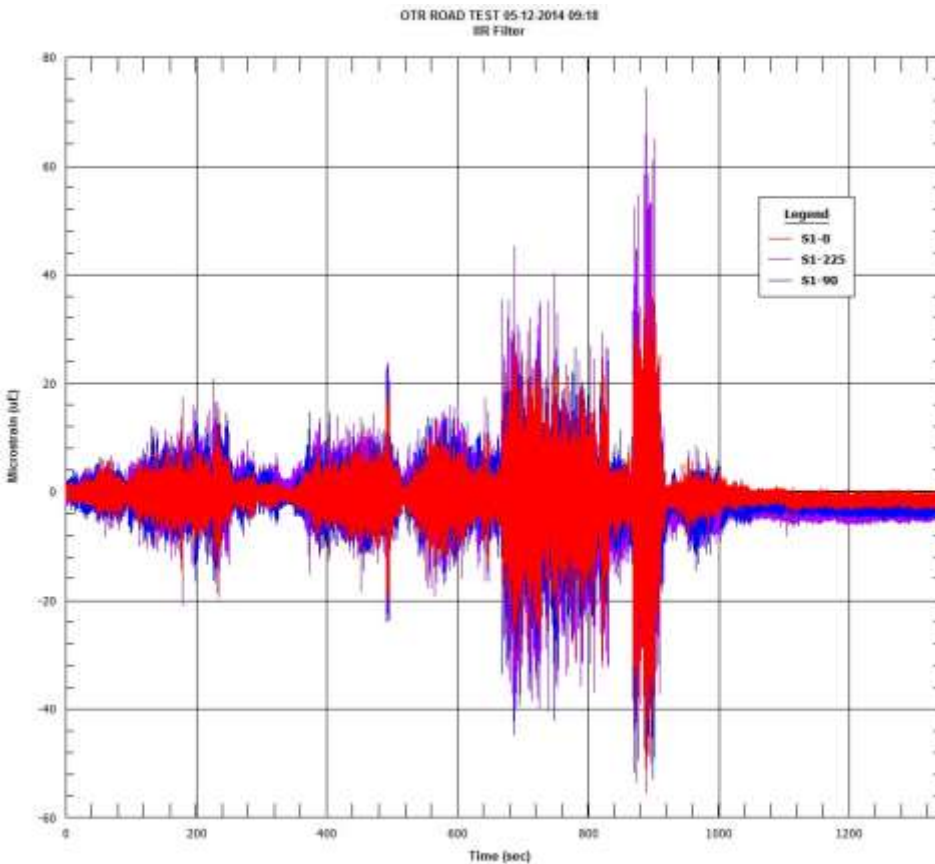
Strains correlated with road conditions

Strains correlated to road surfaces



Rod Strains and FFT

maximum strains occurred at low Hz



Side Basket Showing Cutout for Filming Assembly during Truck Test




Langweilig Video of Assembly during the Truck Test



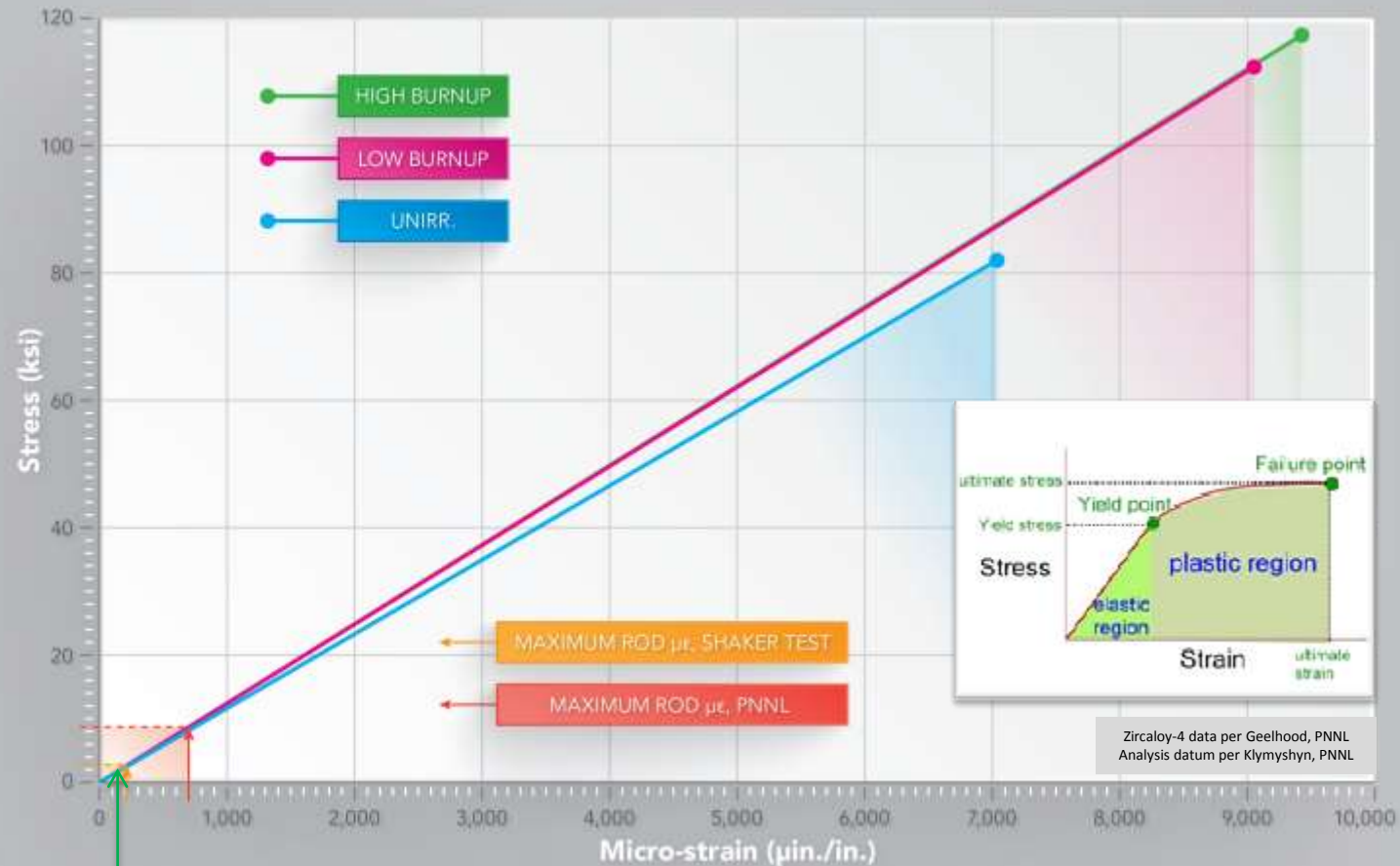
Maximum Strains Measured during Truck Test

similar to shaker results

Strain Gauge	Location on Assembly	Maximum Micro-strain Absolute Value ($\mu\text{in./in.}$)	Road Segment
S1 - 0°	Adjacent to first spacer grid, Span 10	55	
S1 - 90°		53	
S1 - 225°		74	
S2 - 0°	Mid-span, Span 10	94	
S2 - 90°		99	
S2 - 225°		86	
S3 - 0°	Adjacent to first spacer grid, Span 5	143	
S3 - 90°		84	
S3 - 225°		108	
S4 - 0°	Mid-span, Span 5	69	
S4 - 90°		101	
S4 - 225°		93	
Average 0°		90	1
Average 90°		83	
Average 225°		90	

All maximum strains during road Segment #1 at 872.4 – 902.3 seconds into the trip. This corresponds to travel on Poleline Road (dirt).

Measured Strains are Very Low Relative to the Elastic Limit of Zircaloy-4



MAXIMUM STRAIN TRUCK TEST $\approx 143 \mu\text{in./in.}$

Irradiated rods would experience lower strains during truck test than unirradiated tube

- Bending stiffness (=EI) of high burnup irradiated Zircaloy-4 with pellet-clad interaction (per ORNL):

$$EI_{\text{Zirc4-irr}} = 52 \text{ N-m}^2 \quad (\text{I based upon } \underline{\text{rod}} \text{ geometry})$$

$$E_{\text{Zirc4-irr}} = 83 - 101 \text{ GPa}$$

- Bending stiffness of unirradiated Zircaloy-4 tube:

$$EI_{\text{Zirc4-unirr}} = 15.9 \text{ N-m}^2 \quad (\text{I based upon } \underline{\text{tube}} \text{ geometry})$$

$$E_{\text{Zirc4-unirr}} = 99 \text{ GPa}$$

- Bending stiffness Zircaloy-4 (irradiated rod/unirradiated tube) = $52/15.9 = 3.27$

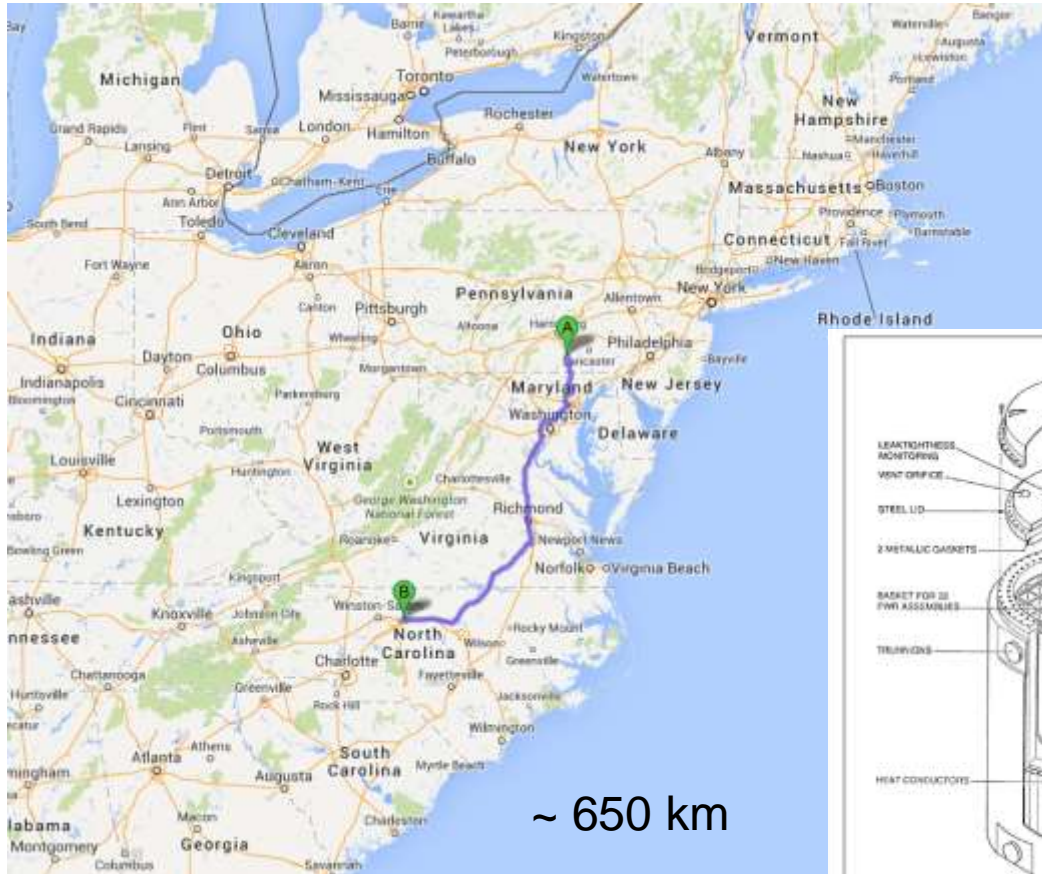
This implies that for a given applied moment, strains on an irradiated rod would be approximately 0.3 ($1/3.27$) of those on an unirradiated Zircaloy-4 tube.

The maximum strain measured on the Zircaloy-4 tube in the truck test was $147 \mu\text{m/m}$, so for the same applied loads, the strain on an irradiated rod would be:

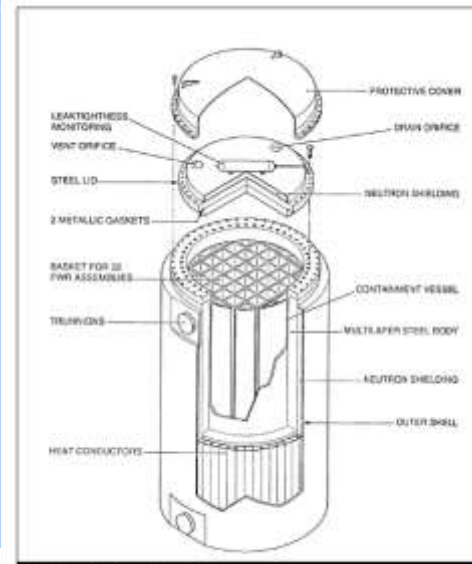
$$147(15.9/52) = 45 \mu\text{m/m}$$

Rail Test Options

TN-32 cask transport from Pennsylvania to North Carolina



North Anna ISFSI



TN-32 Used Fuel Storage Cask



Rail Test Options

- NLI-10/24 cask tests at Tri-City Railroad near PNNL



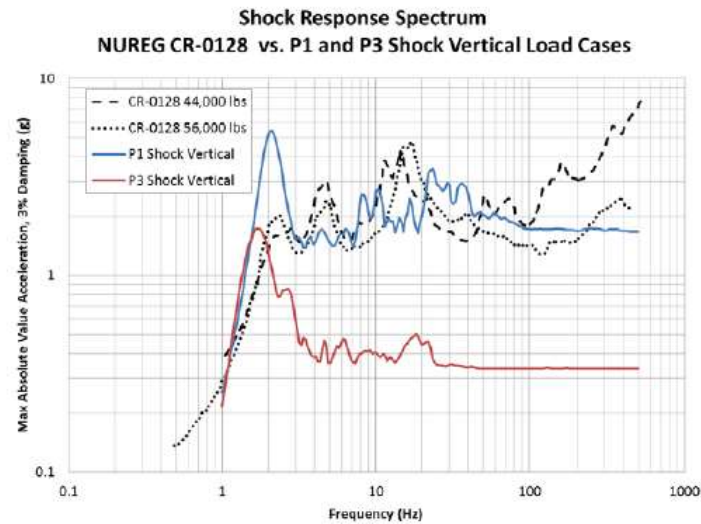
Augusta, Georgia

TCRY Railyard

Richland, Washington

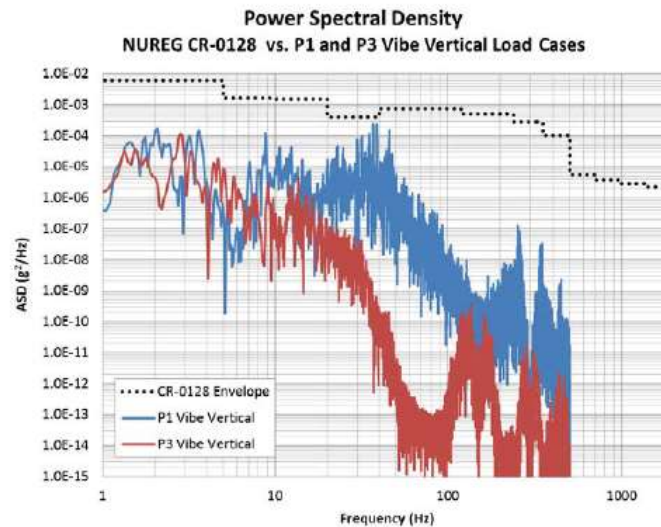
- Controlled test environment
- Variety of track conditions
- Repeatability





(a) Shock

Rail loadings less severe
 than truck loads



(b) Vibration

Figure 5.15 Comparison of the P1 and P3 Load Cases with the NUREG/CR-0128 Shock and Vibration Load Environments

Fracture Mechanics & Fatigue Assessments Based Upon Experimentally-Measured Strains

Crack depth/Zircaloy wall thickness	Applied stress intensity at crack tip, (MPa-√m)	Lower bound Zircaloy-4 fracture toughness, (MPa-√m)
0.10	0.3	20 - 30
0.25	0.4	
0.50	0.6	

